NASA Technical Memorandum 107007

/N-39
3037

Cyclic Load Effects on Long Term Behavior of Polymer Matrix Composites

A.R. Shah
NYMA, Inc.
Brook Park, Ohio

and

C.C. Chamis
Lewis Research Center
Cleveland, Ohio

Prepared for the
40th International SAMPE Symposium and Exhibition
sponsored by the Society for the Advancement
of Materials and Process Engineering
Anaheim, California, May 8–11, 1995

National Aeronautics and
Space Administration

CYCLIC LOAD EFFECTS ON LONG TERM BEHAVIOR OF POLYMER MATRIX COMPOSITES

A. R. Shah
NYMA, Inc.
Brook Park, Ohio

and

C. C. Chamis
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

SUMMARY

A methodology to compute the fatigue life for different ratios, r, of applied stress to the laminate strength based on first ply failure criteria combined with thermal cyclic loads has been developed and demonstrated. Degradation effects resulting from long term environmental exposure and thermo-mechanical cyclic loads are considered in the simulation process. A unified time-stress dependent multi-factor interaction equation model developed at NASA Lewis Research Center has been used to account for the degradation of material properties caused by cyclic and aging loads. Effect of variation in the thermal cyclic load amplitude on a quasi-symmetric graphite/epoxy laminate has been studied with respect to the impending failure modes. The results show that, for the laminate under consideration, the fatigue life under combined mechanical and low thermal amplitude cyclic loads is higher than that due to mechanical loads only. However, as the thermal amplitude increases, the life also decreases. The failure mode changes from tensile under mechanical loads only to the compressive and shear at high mechanical and thermal loads. Also, implementation of the developed methodology in the design process has been discussed.

INTRODUCTION

High speed civil transport (HSCT) engine/structure components are subjected to severe mechanical and thermal cyclic loads. A prime design objective of HSCT components is to assure the safe life of these components under such loading environment. Assessment of component life depends on the behavior of materials used. High temperature polymer matrix composites are being considered as prime candidate materials for some auxiliary HSCT propulsion structure components. Determination and quantification of long term behavior of composite materials is complicated because of its inherent heterogeneity. Therefore, it is important to develop cost effective and efficient methods to predict the life of components made of polymer matrix composite materials. The complexity of predicting composite behavior is compounded by multiple scales (micro, macro, and laminate), fabrication process, constituent materials, and aggressive load environment. Successful utilization of polymer matrix composites in aerospace structures hinges largely upon the ability to predict their long term behavior. The current practice of conducting long term testing of materials and components entails enormous cost and time consumption to capture the effect of all the design variables. Therefore, realization of the full potential of composite materials is not possible without innovative computational approaches capable of handling these aspects in an integrated manner. Also, such computational procedures could aid in identifying critical experiments to be performed as well as reduce the number of tests to be conducted to a manageable proportion.

Traditional computational approaches for life and long term behavior rely on empirical data and are not generic or unique in nature. Also, those approaches are not easy to implement in the design procedure in an effective integrated manner. The focus of ongoing research at the NASA Lewis Research Center has been to develop advanced integrated computational methods and related computer codes to perform a complete reliability based assessment of composite structures. These methods account for uncertainties in all the constituent properties, fabrication process variables, and loads to predict probabilistic micromechanical, ply, laminate, and structural responses. These methods have already been implemented in the Integrated Probabilistic Assessment of Composite Structures (IPACS) computer code (ref. 1). This report deals with the deterministic part of the methodology for combined thermo-mechanical loads. Probabilistic assessments for only mechanical cyclic loads are given in reference 2. The main objective of this report is to illustrate the effectiveness of the methodology to predict the long term behavior of composites under combined mechanical and thermal cyclic loading conditions. A unified time, stress, and load dependent Multi-Factor Interaction Equation (MFIE) model developed at NASA Lewis Research Center (ref. 2) has been used to simulate the long term behavior of polymer matrix composites. The MFIE model evaluates the magnitude of degradation and properties of constituent materials at every time step which in turn is used for micromechanics and laminate analysis. Possible impending failure modes are checked at every time step. The deterministic part of the methodology has been implemented in the in-house computer code ICAN (Integrated Composite Analyzer, ref. 3).

Application of the developed methodology is illustrated by considering a graphite fiber and epoxy matrix composite system. The fatigue life cycle design curves for a $(0/\pm45/90)_s$ graphite/epoxy laminate are computed for different applied stress to laminate strength ratios, *r*, based on first ply failure criteria (hereinafter referred to as laminate strength) under different ambient temperatures and thermal cyclic load amplitudes. These curves can be used to assess the fatigue life of a component subjected to thermo-mechanical cyclic loading. Failure modes governing the life have been identified. Effects of the cyclic thermal load amplitude as well as that of mechanical load have been discussed.

COMPUTATIONAL SIMULATION

Use of fundamental governing field equations in time domain facilitates tracking and understanding the failure mechanism throughout the load history. The approach used herein incorporates the micromechanics theory and time dependent MFIE model to account for the physical process of manufacturing composite material, mechanics governing the individual constituent behavior, their interactions, and degradation due to aggressive load effects. This approach allows tracking the development of the failure mechanism without making any approximations on the actual behavior. The following sections describe the modified computer codes and methodology used in the computational simulation of long term behavior in polymer matrix composites.

Integrated Composite Analyzer (ICAN)

ICAN (ref. 3) computationally simulates the material behavior of polymer matrix composites from fiber/matrix constituents to the laminate scale including fabrication effects (fig. 1). ICAN uses advanced composite micromechanics and laminate theories to compute constituent, ply, and laminate scale properties and stresses required for global structural analysis (left side of fig. 1). ICAN has an updatable resident database containing room temperature properties of commonly available fibers and matrices. All the user needs to do is input the names of fibers and matrices used in the laminate which reduces the time to input the data and eliminates errors. ICAN also synthesizes the global structural response to laminate, ply, and constituent response levels which helps the user evaluate the cause of failure (right side of fig. 1). Details of the ICAN computer code are given in reference 3.

For long term behavior prediction the ICAN computer code was modified to implement time dependence in the MFIE. Also, a failure analysis based on first ply failure and fiber break criteria is performed at every time step to determine whether the laminate can take any further load or not. Failure analysis determines the possible failure modes and maximum load capacity in the respective failure mode. The simulation stops when the laminate is incapable of resisting any more load. Thus, the current ICAN is capable of performing transient analysis to incorporate material degradation caused by thermal and mechanical cyclic loads. Details of MFIE are given the following section.

Time Dependent Multi-Factor Interaction Equation (MFIE) Model

It is known that predicting the behavior of composite materials is a difficult task. Accounting for all the physical effects and how they affect the material properties in time domain is even more complex. Over the years, research in developing a unified law describing the material behavior driven by primitive variables has been an ongoing activity at NASA Lewis Research Center. The result of this research is the development of a unified multi-factor interaction equation (MFIE) model (ref. 4).

Concepts used in reference 4 have been expanded to include the time dependent degradation effect on material behavior due to environmental, fabrication, and load effects (ref. 2). A generic form of the equation that includes those effects is given by

$$\frac{M_p}{M_{po}} = \prod_{i=1}^{N} \left[\frac{V_F - V}{V_F - V_o} \right]_i^a \tag{1}$$

where

M material
V primitive variable affecting the material property

Superscripts:

a exponent for a given primitive variable effect

Subscripts:

p affected material property
i primitive variable index
F condition at the final stage
o condition at the reference stage

Each term in parenthesis accounts for a specific physical effect represented by its respective primitive variable. Any number of effects can be included in a single equation as is readily seen. The exponents are determined from the select experimental data.

An important part of the previous model is the fact that one equation can include all the effects with any nonlinearity in the material behavior. It can describe all the interacting effects of different variables (thermal, metallurgical, mechanical, chemical, and load). Since the variables used are at a primitive level, it simulates the *in situ* degradation in material properties resulting from applied cyclic and environmental effects. The specific form of the equation used in this investigation to account for time dependent degradation is

$$\frac{M_p}{M_{po}} = \left(\frac{T_{gw} - T}{T_{gw} - T_{gd}} \right)^l \left(1 - \frac{\sigma}{S_f} \right)^m \left(1 - \frac{\sigma t}{S_f t_f} \right)^n \left(1 - \frac{\sigma_M N_M}{S_f N_{fM}} \right)^p \left(1 - \frac{\sigma_T N_T}{S_f N_{fT}} \right)^q \tag{2}$$

where

M_p material property subjected to degradation
T temperature
S strength

σ stress
N number of cycles
t time

Superscripts:

l exponent for temperature
m exponent for stress
n exponent for time
p exponent for mechanical cyclic load effect
q exponents for thermal cyclic load effect

Subscripts:

gw wet glass temperature
gd dry glass transition temperature
o reference condition
f final condition
M mechanical cyclic load
T thermal cyclic load

SIMULATION CASES, RESULTS AND DISCUSSION

Demonstration examples include combined mechanical and thermal cyclic loads, as mentioned before. A $(0/\pm45/90)_s$ laminate made of graphite fibers and an epoxy matrix is subjected to uniaxial tensile cyclic as well as thermal cyclic loads as shown in figure 2. Each ply has a thickness of 0.127 mm. The properties of constituent materials and fabrication variables are given in table I. Initially, the laminate was subjected to a uniaxial tensile static load and failure analysis was performed to evaluate static laminate strength. It was found to be 1184 kg/cm. Since the purpose of this study was to develop fatigue life cycles, the laminate was subjected to different applied mechanical stress to strength ratios, *r*. Fatigue life computation of the load cases given in table II were performed to illustrate the behavior of composite materials under the in-phase combined thermo-mechanical cyclic loads as simulated by the modified ICAN. These load cases are divided into three categories. The first category includes only the mechanical cyclic loads (load cases 1, 2, and 3 in table II). The category 2 load cases are for thermal cyclic loads only (load cases 4 to 7 in table II). In category 3 load cases, the mechanical cyclic loads are combined with the thermal cyclic loads of different amplitudes such as 0.0, 15.5, 24.0, 38.0, and 51.7 °C (load cases 8 to 22 in table II). These three categories were chosen to illustrate the effect of thermal and mechanical cyclic loads on the fatigue life.

In each load case simulation, the fatigue life for each ply was computed based upon first ply failure criteria. The shortest life of a ply in the laminate was considered to be the life of a laminate. The results of the first three load cases are summarized in figure 3. This figure shows the variation of fatigue life resulting from mechanical cyclic loads only. The fatigue life in these three cases was primarily governed by failure in 90° ply caused by the transverse tensile stress being greater than the corresponding strength. Thus, the life under uniaxial tensile cyclic loads of that laminate is governed by the transverse tension failure in 90° plies. Figure 3 also shows that the fatigue life under mechanical cyclic loads drops rapidly as the amplitude of applied cyclic stress increases. At load ratios $r = 60$, 70, and 80 percent, the fatigue life is 90, 38, and 15 percent of the endurance limit, N_{fM}, respectively.

Figure 4 depicts the variation of fatigue life with respect to cyclic temperature amplitude (load cases 4 to 7). Fatigue life caused by thermal cyclic loads in the laminate under consideration is mainly governed by the transverse compressive failure in a 45° ply. As shown in the figure, the fatigue life variation is not as severe when it is caused by variation in cyclic temperature amplitude as it is in the case when it results from mechanical load amplitude. The fatigue life for temperature amplitudes of 15.5, 24.0, 38.0, and 51.7 °C is 92, 87, 80, and 73 percent, respectively.

Thermal loads induce compressive stresses in transverse direction of both 45° and 90° plies. Since allowable ply compressive strength is higher than the tensile strength, a higher life is expected under thermal loads.

Figures 5 to 9 contain fatigue life curves under combined thermo-mechanical loading with cyclic temperature amplitudes of 0.0, 15.5, 24.0, 38.0, and 51.7 °C, respectively. These results are very interesting because they enable us to determine the behavior of graphite/epoxy composite material under thermal cyclic loading. It is seen from these figures (and fig. 10) that the fatigue life variation with respect to the applied stress ratio is almost linear up to a cyclic temperature amplitude of 24 °C and becomes nonlinear for temperature amplitudes above 24 °C. This is due to the fact that, at low temperature amplitudes, the failure is mostly governed by the longitudinal compressive strength in a 90° ply. However, at higher thermal amplitudes and low load ratio, *r*, the governing failure mode shifts from 90° ply to 45° ply with compressive strength in the transverse direction being the limiting factor. Also, at high load ratio, *r*, and higher temperature amplitudes, the failure mode is controlled by the shear strength in a 45° ply. Thus when the shear mode failure controls the behavior, the drop in life is also steep with an increase in load ratio, *r*.

Figure 10 shows that the fatigue life under mechanical cyclic loads is higher than that with combined low amplitude thermo-mechanical cyclic loads. But, as the temperature amplitude increases with the mechanical loads, the life decreases. The reason for this is that in failing plies the tensile stresses resulting from mechanical loads are modified by the compressive stresses caused by thermal loads. Thus, the failure mode changes from tension to compression. However, the continuing rise in thermal load amplitude increases the compressive stresses and thus results in decreased life. In general for the laminate under consideration, the fatigue life under combined mechanical and low thermal amplitudes is higher than that resulting from mechanical loads only.

The information in figures 3 to 10 can be used as a design aid to determine the component life as well as to make decisions on its continuing use. Similar design curves can be developed readily for any polymer matrix composite with any laminate configuration and for any load condition. Further work on developing reliability based fatigue life design curves is underway. A reliability based approach provides the level of reliability of a given design as well as identifying the controlling variables. Thus, it helps improve the manufacturing process, design experiments, and develop inspection guidelines.

CONCLUSION

A methodology to simulate the cyclic load effect on the long term behavior and fatigue life of polymer matrix composites has been developed, implemented in the in-house computer code ICAN, and demonstrated by examples. A main feature in this methodology is a generic time dependent multi-factor interaction equation (MFIE) model. Also, the methodology has been implemented in ICAN to facilitate its future integration with the IPACS computer code to perform probabilistic composite structural analysis. Fatigue life cycle curves for a $(0/\pm45/90)_S$ graphite/epoxy laminate under uniaxial tensile and thermal loads were simulated. It was observed that the life of a laminate with low amplitude thermal loads is higher than that under mechanical cyclic loads. Also at low thermal cyclic load amplitudes, the variation of fatigue life with respect to load ratio, *r*, is linear and decreases mildly as *r* increases. Whereas at high thermal amplitudes, it becomes highly nonlinear and decreases rapidly in life as *r* increases. At low thermal cyclic amplitude loads, the failure is governed by transverse compressive strength in 90° plies. On the other hand, at high thermal cyclic amplitudes and high load ratios, it is governed by shear failure in 45° ply.

REFERENCES

1. Integrated Probabilistic Assessment of Composite Structures (IPACS) User's Manual. Ver. 1.0. NASA Contract No. NAS3–25266, Task Order 5209–02, Dec. 1991.
2. Shah, A.R., et al.: Probabilistic Simulation of Long Term Behavior in Polymer Matrix Composites. AIAA Paper 94–1445, April 1994.

3. Murthy, P.L.N.; and Chamis, C.C.: Integrated Composite Analyzer (ICAN): Users and Programmers Manual, NASA TP–2515, March 1986.
4. Boyce, L.; and Chamis, C.C.: Probabilistic Constitutive Relationships for Cyclic Material Strength Models. Proceedings of the 29th AIAA Structures, Structural Dynamics, and Materials Conference, pt. 3, J. Propul. P., 1988, pp. 1299–1306.

TABLE I.—CONSTITUENT PROPERTIES

Fiber	
Normal Modulus, E_{f11}, GPa	213.7
Normal Modulus, E_{f22}, GPa	13.8
Poisson's ratio, ν_{12}	0.20
Poisson's ratio, ν_{23}	0.25
Shear Modulus, G_{f12}, GPa	13.8
Shear Modulus, G_{f23}, GPa	6.9
Tensile strength, S_{fT}, GPa	2.8
Compressive strength, S_{fC}, GPa	2.8
Matrix	
Normal Modulus, E_m, GPa	3.4
Poisson's ratio, ν_m	0.35
Tensile strength, S_{mT}, GPa	0.1
Compressive strength, S_{mC}, GPa	0.24
Shear strength, S_{mS}, GPa	0.09
Fabrication variables	
Fiber volume ratio, percent	60
Void volume ratio, percent	2
Ply thickness, mm	0.127

TABLE II.—FATIGUE LIFE COMPUTATION LOAD CASES

Case number	Mechanical cyclic load ratio, r	Mean temperature, °C	Cyclic temperature, °C
1	0.6	21.1	0.0
2	0.7	21.1	0.0
3	0.8	21.1	0.0
4	0.0	65.6	15.6
5	0.0	65.6	23.9
6	0.0	65.6	37.8
7	0.0	65.6	51.7
8	0.6	65.6	0.0
9	0.7	65.6	0.0
10	0.8	65.6	0.0
11	0.6	65.6	15.6
12	0.7	65.6	15.6
13	0.8	65.6	15.6
14	0.6	65.6	23.9
15	0.7	65.6	23.9
16	0.8	65.6	23.9
17	0.6	65.6	37.8
18	0.7	65.6	37.8
19	0.8	65.6	37.8
20	0.6	65.6	51.7
21	0.7	65.6	51.7
22	0.8	65.6	51.7

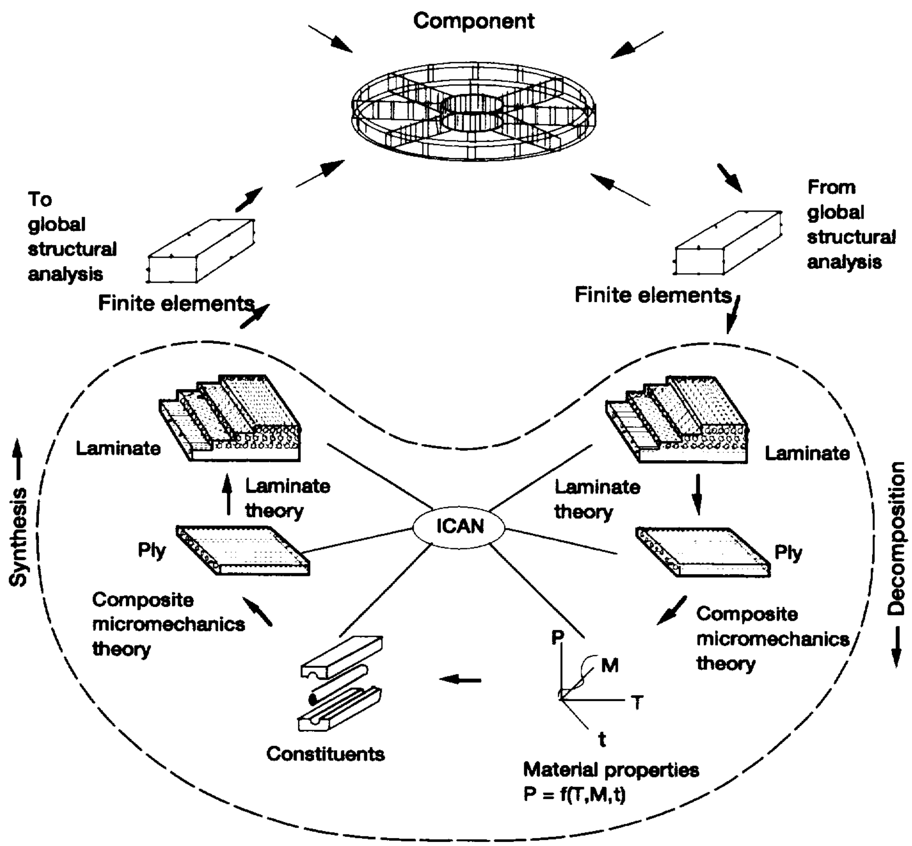

Figure 1.—Schematic of ICAN computer code.

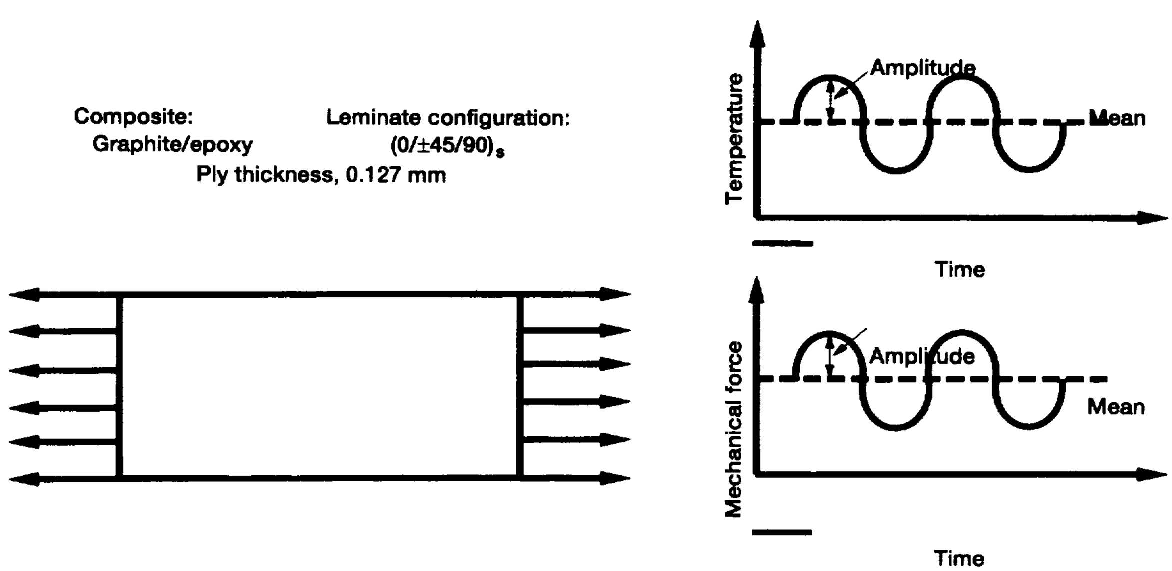

Figure 2.—Description of thermo-mechanical cyclic load.

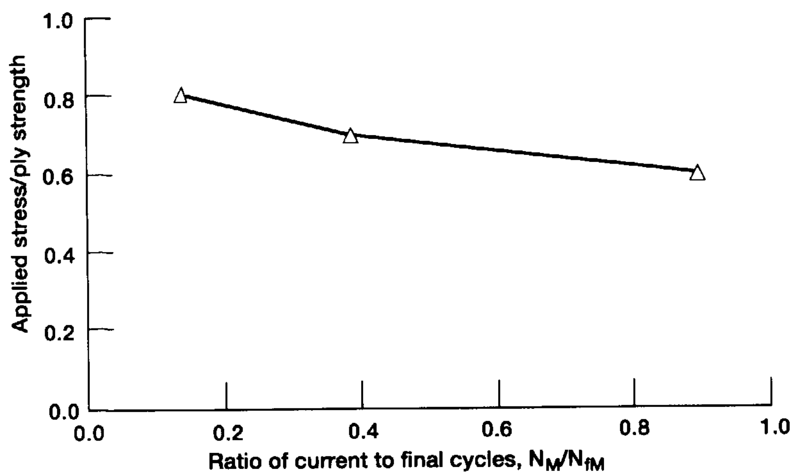

Figure 3.— Fatigue life variation resulting from mechanical cyclic load. Mean applied load, 80 percent of ply strength.

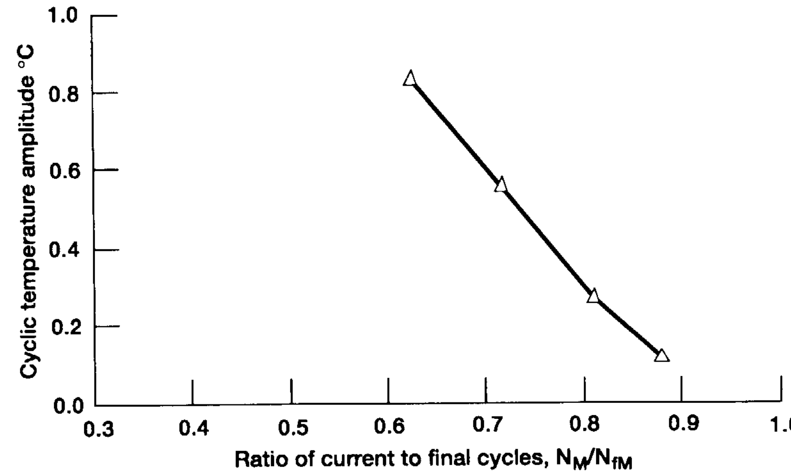

Figure 4.—Fatigue life variation resulting from thermal cyclic load. Mean applied load, 50 percent of ply strength; mean temperature, 65.5 °C; cyclic mechanical load, 0.0.

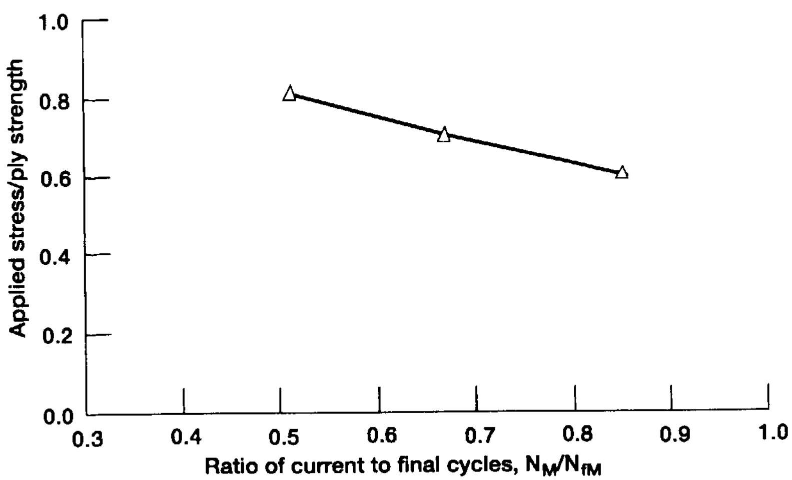

Figure 5.— Fatigue life variation resulting from mechanical cyclic load at constant temperature. Mean applied load, 50 percent of ply strength; mean temperature, 65.5 °C; cyclic temperature load, 0.0 °C.

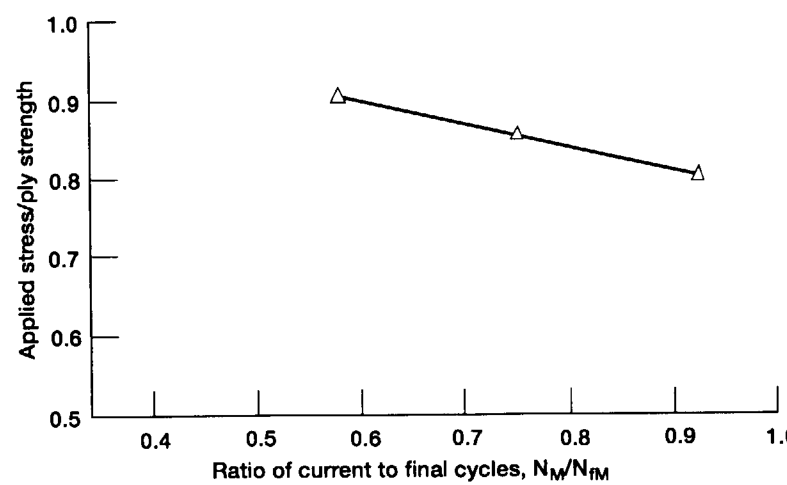

Figure 6.— Fatigue life variation resulting from thermo-mechanical cyclic load, 50 percent of ply strength; mean temperature, 65.5 °C; cyclic temperature, 15.5 °C.

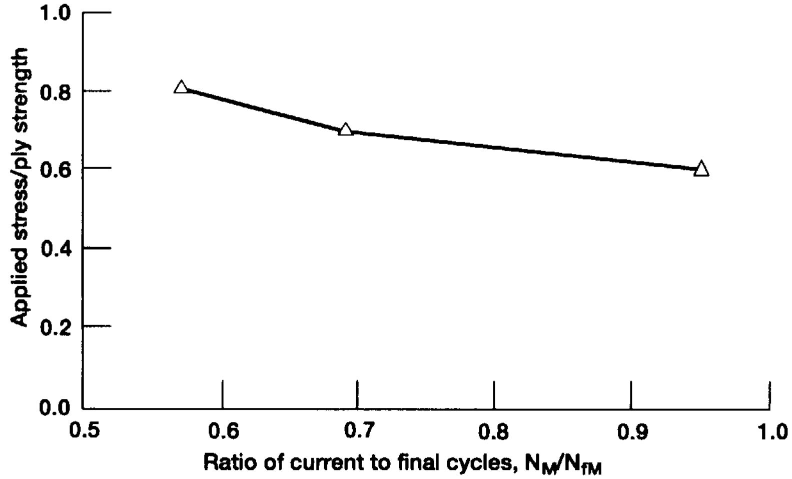

Figure 7.—Fatigue life variation resulting from thermo-mechanical cyclic load. Mean applied load, 50 percent of ply strength; mean temperature, 65.5 °C; cyclic temperature, 24.0 °C.

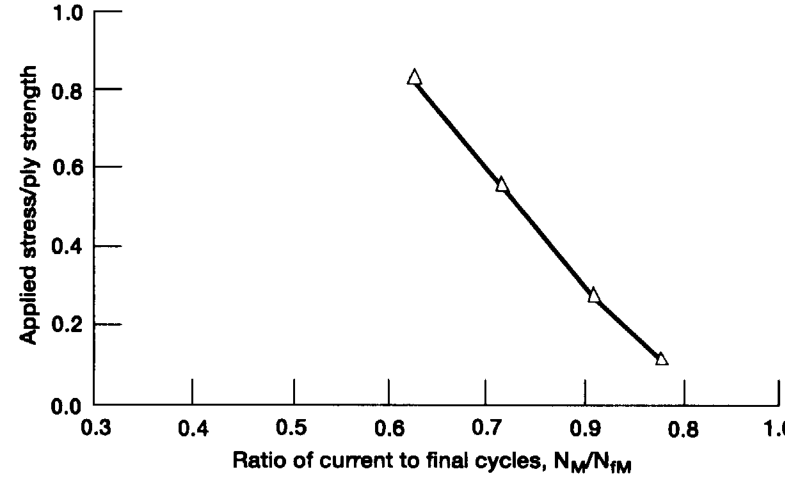

Figure 8.—Fatigue life variation resulting from thermo-mechanical load. Mean applied load, 50 percent of ply strength; mean temperature, 65.5 °C; cyclic temperature, 38.0 °C.

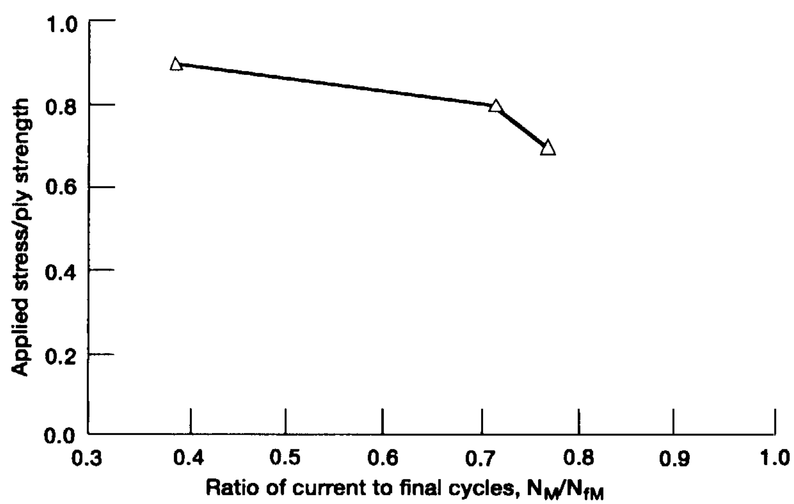

Figure 9.— Fatigue life variation resulting from thermo-mechanical cyclic load. Mean applied load, 50 percent of ply strength; mean temperature, 65.5 °C; cyclic temperature 51.7 °C

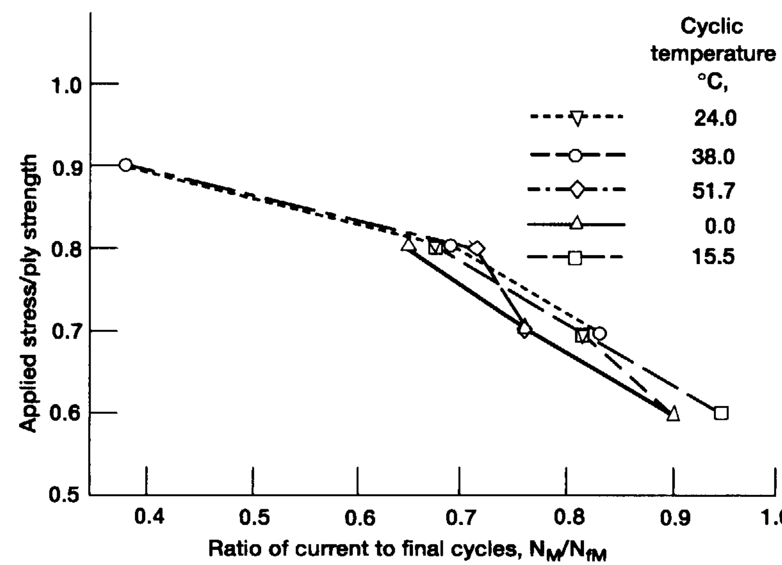

Figure 10.—Fatigue life variation resulting from thermo-mechanical cyclic load. Mean applied load, 50 percent of ply strength; mean temperature, 65.5 °C.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
March 1996

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Cyclic Load Effects on Long Term Behavior of Polymer Matrix Composites

5. FUNDING NUMBERS
WU-505-62-10

6. AUTHOR(S)
A.R. Shah and C.C. Chamis

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-9791

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-107007

11. SUPPLEMENTARY NOTES
Prepared for the 40th International Symposium and Exhibition sponsored by the Society for the Advancement of Materials and Process Engineering, Anaheim, California, May 8-11, 1995. A.R. Shah, NYMA, Inc., Brook Park, Ohio 44142 (work funded by NASA Contract NAS3-27186) and C.C. Chamis, NASA Lewis Research Center. Responsible person, C.C. Chamis, organization code 5200, (216) 433-3252.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 39

This publication is available from the NASA Center for Aerospace Information, (301) 621-0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

A methodology to compute the fatigue life for different ratios, r, of applied stress to the laminate strength based on first ply failure criteria combined with thermal cyclic loads has been developed and demonstrated. Degradation effects resulting from long term environmental exposure and thermo-mechanical cyclic loads are considered in the simulation process. A unified time-stress dependent multi-factor interaction equation model developed at NASA Lewis Research Center has been used to account for the degradation of material properties caused by cyclic and aging loads. Effect of variation in the thermal cyclic load amplitude on a quasi-symmetric graphite/epoxy laminate has been studied with respect to the impending failure modes. The results show that, for the laminate under consideration, the fatigue life under combined mechanical and low thermal amplitude cyclic loads is higher than that due to mechanical loads only. However, as the thermal amplitude increases, the life also decreases. The failure mode changes from tensile under mechanical loads only to the compressive and shear at high mechanical and thermal loads. Also, implementation of the developed methodology in the design process has been discussed.

14. SUBJECT TERMS
Composite; Fiber; Matrix; Cycles; Fatigue; First ply failure; Fatigue life; Multi-factor interaction equation

15. NUMBER OF PAGES
12

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT

National Aeronautics and
Space Administration
Lewis Research Center
21000 Brookpark Rd.
Cleveland, OH 44135-3191

Official Business
Penalty for Private Use $300

POSTMASTER: If Undeliverable — Do Not Return